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STATISTICAL MEASUREMENTS OF DEFORMATION STRUCTURES AND REFRACTIVE
INDICES IN EXPERIMENTALLY SHOCK LOADED QUARTZ

By

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STATISTICAL MEASUREMENTS OF DEFORMATION STRUCTURES AND REFRACTIVE INDICES IN EXPERIMENTALLY SHOCK LOADED QUARTZ¹

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Shock loading experiments were conducted on natural single quartz crystals using a 20 mm powder gun. Specimens cut parallel to the crystallographic planes {0001}, {10 $\bar{1}$ 0} and {10 $\bar{1}$ 1} were shock-loaded to pressures approaching 270 kb. A variety of shock features known from naturally shocked rocks were reproduced.

"Cleavage" is produced by shock pressures as low as 50 kb and develops predominantly on crystallographic planes with high resolved shear stress. Shocks propagating perpendicular to {0001} and {10 $\bar{1}$ 0} produce these structures parallel to the unit rhombohedron; shocks propagating perpendicular to {10 $\bar{1}$ 1} yielded cleavages parallel to base and prism. This suggests, at least in the present experiments, that the formation mechanism for these features is actually faulting and that they are not cleavages *sensu strictu* but faults.

"Planar features" develop at pressures above 100 kb. Regardless of impact direction they cluster predominantly near {10 $\bar{1}$ 3}. At pressures above 180 kb they are also strongly developed on {10 $\bar{1}$ 2}. It appears that their formation is only possible in the plastic region of the quartz Hugoniot equation of state. The actual mechanism of their formation is not yet known.

Refractive index measurements indicate that the breakdown of the quartz lattice to an amorphous state occurs gradually over a wide pressure range from about 200 kb to above 300 kb.

INTRODUCTION

Shock-deformed quartz is well known from rocks associated with terrestrial meteorite craters, structures of suspected impact origin, and nuclear and chemical explosion sites. It has also been produced in laboratory shock-loading experiments. An empirical correlation of shock pressure and shock damage in terms of microdeformation structures and phase transitions has been established by various petrographers (Stöf-

fler, 1966; Short, 1966; Chao, 1967a, 1967b, *this vol.*, p. 135; Dence, *this vol.*, p. 169; Engelhardt and Stöffler, *this vol.*, p. 159; Robertson *et al.*, *this vol.*, p. 433.). Although the various stages of shock metamorphism have been well documented, there are few data available relating specific shock features to the pressure (and temperature) history of the sample. It is possible to simulate, to a certain extent, natural impact conditions in the laboratory by making use of methods developed in the study of the high pressure physics of solids. Controlled shock loading experiments are necessary for a more detailed understanding and interpretation of naturally shocked quartz.

This paper presents an attempt to experimentally reproduce deformation structures in quartz that are considered indicative of shock loading during meteorite impact (Bunch and Cohen, 1964;

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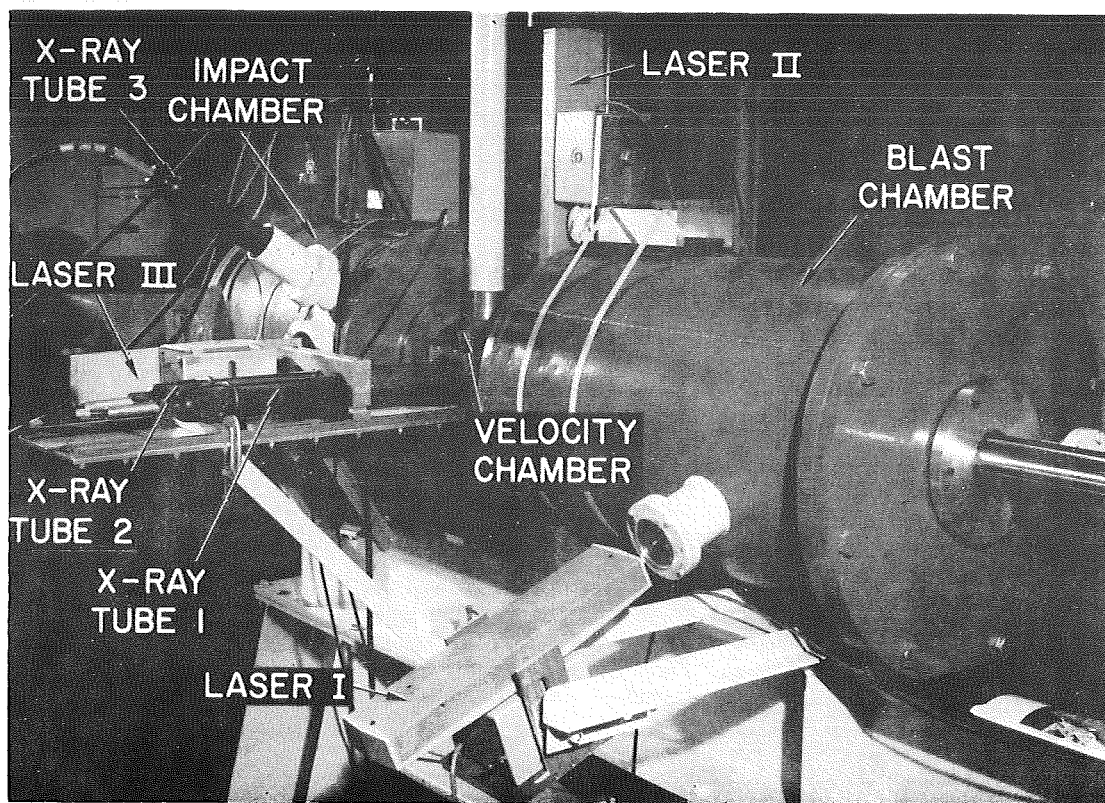


Fig. 1. 20 mm powder gun used to accelerate projectiles (total length: 3.5 m).

Engelhardt and Stöffler, 1965; Carter, *this vol.*, p. 453; Chao, *this vol.*, p. 135; Bunch *et al.*, *this vol.*, p. 509; Engelhardt *et al.*, *this vol.*, p. 475; Gold, *this vol.*, p. 495; Robertson *et al.*, *this vol.*, p. 433; Sclar *et al.*, *this vol.*, p. 483; Short and Bunch, *this vol.*, p. 255.). The various types of deformation features in quartz, their crystallographic orientation, and their statistical distributions might be sensitive indicators of the pressure-temperature history of the recovered sample. In addition, controlled experiments are needed to demonstrate the gradual collapse of the quartz lattice under shock conditions as observed in naturally shocked rocks (see authors above).

This preliminary report presents only the experimental methods and results. Without further investigations, the proper interpretation and correct application of the experimental data to naturally shocked rocks is not possible, nor will they be compared in this paper with static experi-

ments and rocks deformed under tectonic stress and strain rates.

SHOCK LOADING EXPERIMENTS

A number of techniques are available for shock loading solids. The most common methods involve the acceleration of a "driver" plate to high velocities. The impact of the "driver" plate with the target material generates a shock wave. A small ballistic range was used in this work as the accelerating mechanism (20 mm powder gun, Fig. 1).

20 mm Powder Gun

The projectile is propelled by conventional gun powders and is timed during flight by a combination of He/Ne continuous gas lasers, photodiodes, and a ten-digit, dual-time interval meter. X-ray shadowgraph techniques project a

picture of the flying projectile against a fiducial grid, thus allowing an additional time check. Two horizontal x-ray flash tubes, and one inclined at 60° , monitor the projectile tilt. The velocities are measured with an accuracy of $\pm 1\%$.

Target

All targets used were discs 10 mm in diameter and 1–2 mm thick, cut from the same natural untwinned quartz crystal. Since the relation of the shock propagation direction to crystallographic orientation is of special interest, target specimens cut in three differently oriented crystallographic directions were shock loaded. Cuts were made parallel to the base $\{0001\}$, the prism $\{10\bar{1}0\}$, and the unit rhombohedron $\{10\bar{1}1\}$. All three cuts were in the crystallographic zone $[10\bar{1}0]$. Each target was oriented with an accuracy of $\pm 1^\circ$, using a Laue X-ray Polaroid camera.

The small discs were embedded in a cylindrical KBr pellet (25 mm diameter, 30–50 mm long). The pressed KBr has a density of 2.64–2.66 g/cm³ and provides an ideal impedance match for quartz. The pellet was then mounted in an aluminum container. Four set screws held it in place and allowed accurate aligning with respect to the projectile's flight path.

After impact, the fragmented mixture of KBr and target material was collected. The KBr was dissolved in H₂O, and the shocked quartz was recovered as a fine powder with grain sizes ranging from less than one micron to 1–2 mm, with an average being between 0.5–1 mm. For the optical investigations, powder mounts made from the grain size fraction 250–350 μ were used.

Pressure Calculations

If the equations of state are known for both the driver and target materials, a simple graphical solution (Fig. 2) yields the pressure generated in the target, using the boundary conditions $V_i = u_{pp} + u_{pt}$. V_i is the impact velocity of the projectile, u_{pp} and u_{pt} are the shock particle velocities in projectile and target respectively. Three materials having different densities and for which equation of state data are known were selected as driver plates. The materials are Lexan

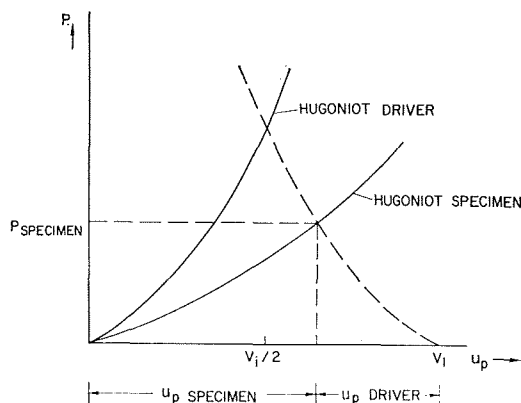


Fig. 2. Impedance match method for determining shock pressures. The driver's equation of state is reflected at V_i (dashed curve). The intersection of this curve with the specimen's Hugoniot curve gives the pressure generated in the specimen (u_p = particle velocity).

(Isbell, Shipman, and Jones, 1966), 2024 aluminum (Thiel, 1966) and Fansteel "77H" (Jones, Isbell, and Maiden, 1965).

The equation of state data of Wackerle (1962), Ahrens and Gregson (1964), and Fowles (1967), were used to calculate the pressures in the quartz target. However, these data were obtained with quartz plates oriented with respect to rectangular engineering coordinates x , y , and z ($x = \{2\bar{1}\bar{1}0\}$, $y = \{01\bar{1}0\}$, $z = \{0001\}$). Therefore both $\{10\bar{1}0\}$ and $\{10\bar{1}1\}$ directions in this work were calculated using the x -cut; for $\{0001\}$ the z -cut was taken.

Excluding this necessary compromise, but including all experimental tolerances and sources of errors, the extrapolated shock pressures are believed accurate to $\pm 5\%$, which is considered satisfactory for geological interpretations.

DEFINITION OF MICRODEFORMATIONS

Unusual and unique microdeformations are characteristic of the component minerals in rocks associated with impact structures. Quartz in particular displays a variety of "planar elements" or "planar features" arranged in single or multiple sets (see various papers in this symposium). The nature and origin of these unusual structures is not fully understood, but they seem to be indicative of shock loading. Carter (1965, *this*

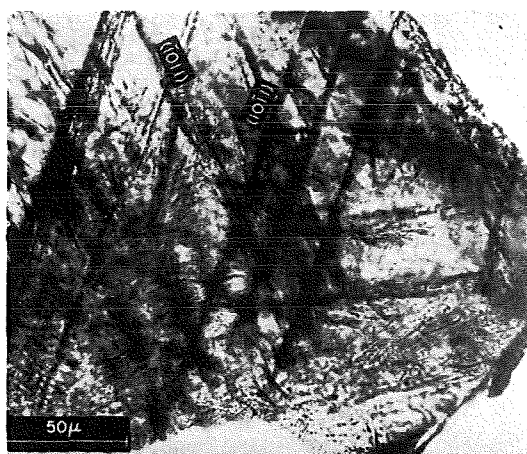


Fig. 3. Experimentally produced "cleavages" (119 kb, $\perp$ {0001}). (Figures in parentheses are the calculated shock pressure and the crystallographic orientation of the quartz target specimen.)

vol., p. 453) has shown, using optical methods (bright field and phase contrast illumination), that it is possible to distinguish four distinct types of features: (a) "cleavage", (b) "faults", (c) "planar features" and (d) "basal deformation lamellae". With the qualifications discussed below, it was found that all these features were produced in these experiments.

"Cleavage"

For the statistical measurements in this work, standard universal-stage techniques were used.

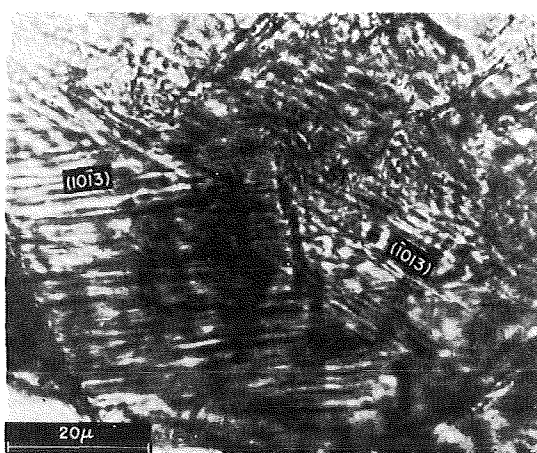


Fig. 4. Experimentally produced "planar features" (162 kb, $\perp$ {0001}).

Because all the measurements were performed with powder mounts, there was no possibility of resolving "cleavages" and "faults". Faults can be recognized only in thin sections, where the original grain boundaries are preserved. Aside from the presence or absence of offsets, there are no optical means to distinguish a cleavage plane from a fault. For this particular study, the term "cleavage" therefore combines cleavages and faults (as distinguished by Carter) and is applied to features (Fig. 3) which: (a) are comparatively broad (2–10 μ wide); (b) are widely spaced (generally 20 μ or more apart from each other;

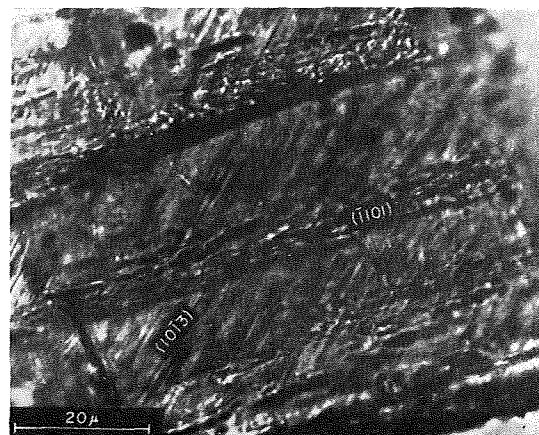


Fig. 5. Combination of shock-produced "cleavage" {10 $\bar{1}$ 1} and "planar features" {10 $\bar{1}$ 3} (162 kb, $\perp$ {0001}). Note that the cleavage "plane" is tilted and cuts through the grain.

(c) exhibit symmetrical extinction and symmetrical movement of the Becke line when the cleavage is oriented parallel to the microscope axis; (d) are commonly visible cutting through the grain (clearly three dimensional features). Sometimes the grains have a zig-zag outline which indicates that the quartz lattice yielded parallel to these planes.

"Planar Features"

The distinction between "planar features" and "basal deformation lamellae" is difficult and must be done under phase contrast illumination. However, phase contrast illumination requires flat stage operations, and therefore only a limited amount of grains present are suitable for investi-

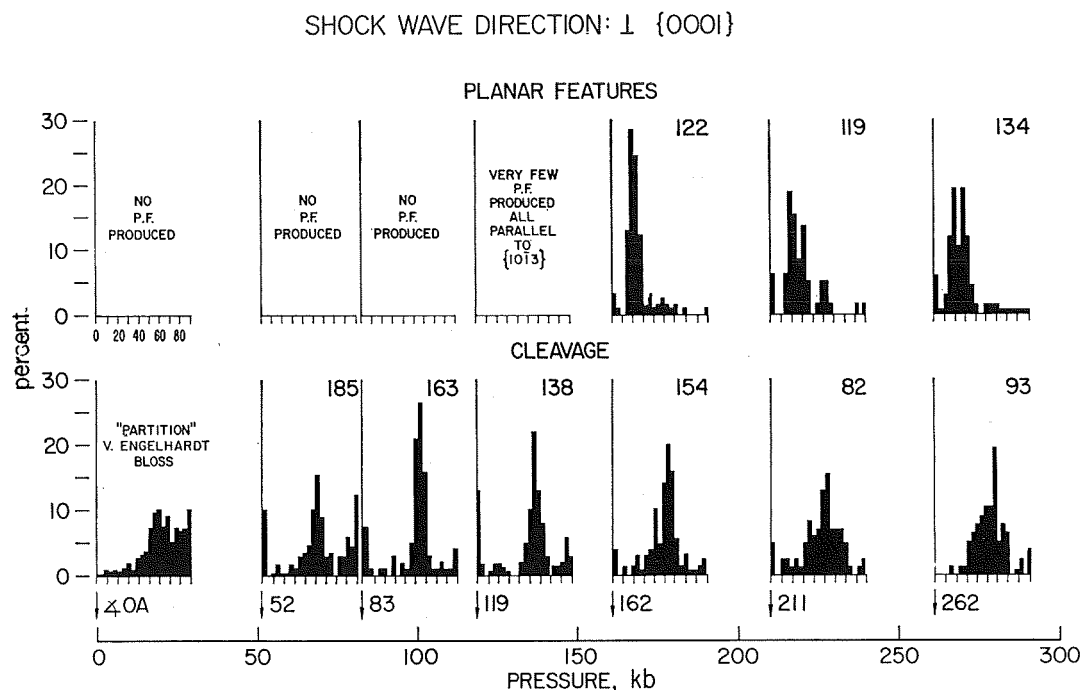


Fig. 6. Angles between optic axes and poles to cleavages and planar features produced in quartz at various shock pressures. Shock wave direction: $\perp$ {0001}. Each histogram represents an individual shot. Histograms of cleavage and planar features shown at identical sites on the pressure axis are from identical samples. Numbers next to arrows indicate exact pressure; numbers in upper right hand corner of each histogram give numbers of measurements per histogram. Percentages are given in percentage of counts.

gations, namely, those in which the feature in question is exactly parallel to the microscope tube. This condition only rarely occurs, because in general the features are randomly tilted; and then, a distinction between "planar features" and "deformation lamellae" with phase contrast and flat stage is not usually possible. Reliable statistics are not readily obtained. Owing to the small amount of material available this was impossible in the present study. In addition, early measurements revealed that only a very small percentage ($\approx 1\%$) of the features produced could be identified as true deformation lamellae. Consequently, for the statistical evaluation of the orientation of "planar features", it was not necessary to distinguish them from deformation lamellae in order to preserve statistical accuracy. Carter's "planar features" and "deformation lamellae" were therefore combined in this work as "planar features" (Fig. 4), which are defined as follows: (a) they are very thin planar

structures ($1-2 \mu$ or less in width); (b) they are very closely spaced ($2-5 \mu$ apart); (c) they occur exclusively in sets of more than 5 individuals (at relatively low pressures); (d) they occur in multiple sets and many more individuals at higher pressures. Figure 5 shows "cleavage" and "planar features" in the same grain to illustrate their distinction.

EXPERIMENTAL RESULTS

The orientation of the deformation features with regard to the optic axis and the angular relations between the features themselves (if more than one set were present) were measured in individual grains. Only measurements for inclinations to the optic axis are presented here (Figs. 6, 7 and 8). These histograms could be somewhat misleading insofar as they include all measurements of both rational (90-95%) and irrational (5-10%) planes. In addition, it is not

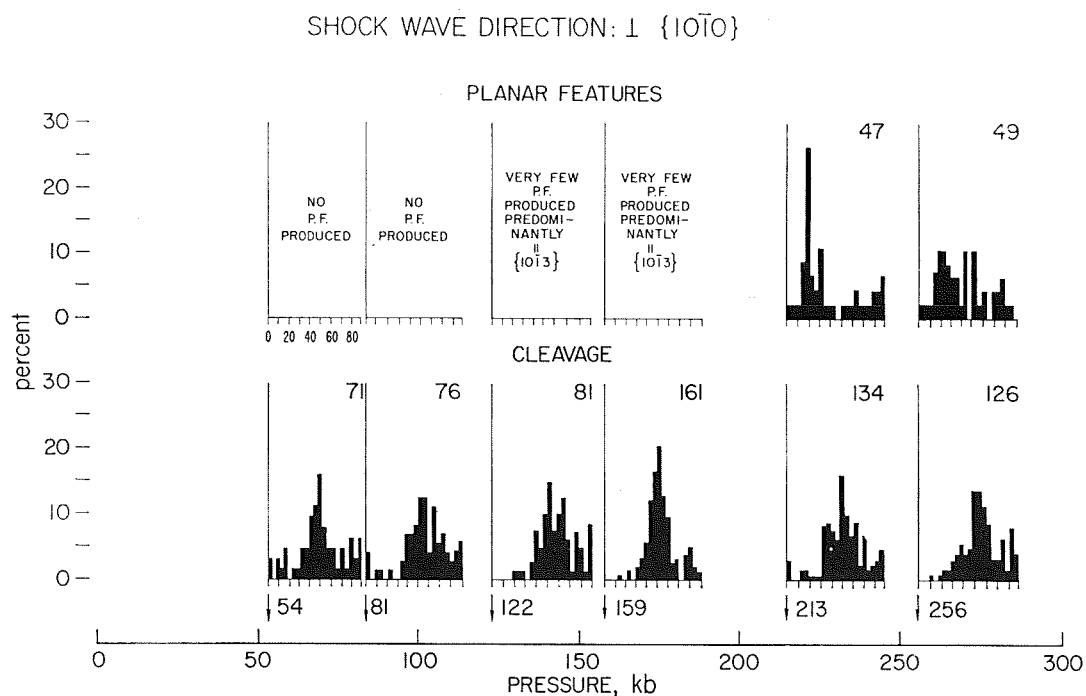


Fig. 7. Angles between optic axes and poles to cleavages and planar features produced in quartz at various shock pressures. Shock wave direction: $\perp \{10\bar{1}0\}$ (same arrangement of diagrams as in Fig. 6).

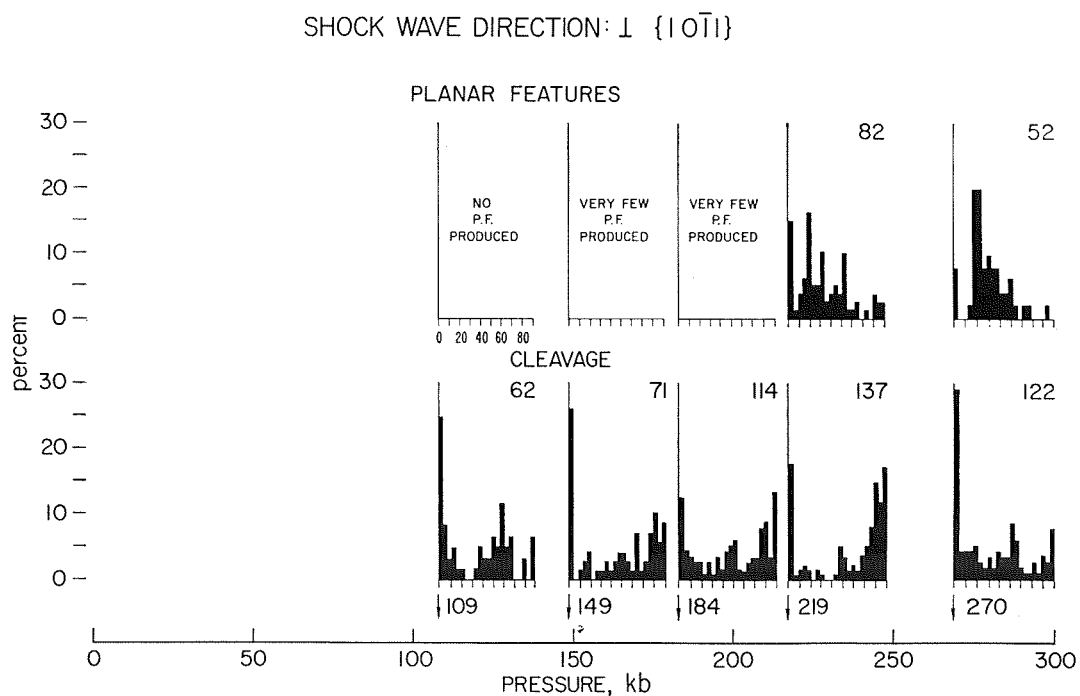


Fig. 8. Angles between optic axes and poles to cleavages and planar features produced in quartz at various shock pressures. Shock wave direction: $\perp \{10\bar{1}1\}$ (same arrangement of diagrams as in Fig. 6).

sufficient to "identify" a crystallographic plane only by its inclination to the optic axis. A three dimensional analysis in which the measured orientations are matched with rational face poles of a quartz stereoplot is required to formulate more definite conclusions. This type of analysis is now being carried out.

Figure 6 contains results of earlier studies, at atmospheric pressure, by Engelhardt (1944) and Bloss (1957). Using a different method they measured the "partition" of quartz, after crushing quartz grains by a variety of techniques. Their distribution histograms display small maxima at the site of the unit rhombohedron (52°) and prism (90°). An identical distribution was observed by Stöffler (1963) in a "Tonstein" (*in situ* kaolinized rhyolitic tuff, Ens Dorf Mine, Germany) which confirmed the experimental work of Engelhardt and Bloss. This distribution curve is representative for the partition (fracturing) of quartz at relatively low stress levels acting during "normal" geologic events.

Quartz that is shock loaded behaves in a markedly different manner, at even comparatively low stress levels (see Figs. 6, 7, and 8). The cleavages display pronounced maxima at the sites of rational lattice planes, predominantly those of the unit rhombohedron (52°), prism (90°), and base (0°). However, the sites of the maxima clearly depend on the orientation of the shock wave with respect to the quartz lattice. Shock waves propagating perpendicular to {0001} and {10 $\bar{1}$ 0} generate cleavages which are primarily parallel to the unit rhombohedron (Figs. 6 and 7) whereas impacts perpendicular to {10 $\bar{1}$ 1} produced cleavages parallel to the base and prism (Fig. 8).

The lowest pressure levels investigated were around 50 kb. Cleavage, though present, is rather sparse relative to the populations produced at higher pressures.

The "planar features" are of greater importance in the interpretation of shock metamorphosed rocks. Figures 6, 7, and 8 show very clearly that the orientation of planar features (relative to the optic axis) is independent of the direction of the propagating shock wave. For three different impact directions, "planar features" cluster primarily around the flat rhombohedrons {10 $\bar{1}$ 3}

(22°) and {10 $\bar{1}$ 2} (32°). Some scatter is caused by poor statistics. Planar features develop more readily and frequently if the impact direction is parallel to the optic axis than they do for the other two orientations. Shocked grains in the former orientation quite frequently display 3–4 different sets of planar features, whereas grains shocked perpendicular to {10 $\bar{1}$ 0} and {10 $\bar{1}$ 1}, even at higher stress levels, rarely have three different sets.

The formation of planar features requires pressures in excess of ~ 100 kb. A test conducted at 97 kb ({0001}) did not yield planar features. Since a shot at 119 kb displayed them, the minimum pressure to produce planar features in single crystals of quartz can be placed between 100 and 120 kb.

The first planar features to appear at low shock pressures are exclusively parallel to {10 $\bar{1}$ 3}. At pressures between 160 and 200 kb, the {10 $\bar{1}$ 2} sets start to appear; this latter orientation becomes almost equally important at higher pressures (see Fig. 7).

Planar features parallel to other less prominent crystallographic planes such as {0001}, {11 $\bar{2}$ 2}, {10 $\bar{1}$ 1}, {11 $\bar{2}$ 1}, {51 $\bar{6}$ 1}, {21 $\bar{3}$ 1} and {10 $\bar{1}$ 0} (or their symmetric equivalents) could be identified in stereoplots. Because these orientations form extremely rarely, they do not appear to be suitable for describing quartz-bearing rocks in terms of progressive shock metamorphism. According to these results, however, they require for their formation pressures in excess of 120 kb, probably in the range of 130–150 kb.

DISCUSSION

The orientation of shock-produced cleavages is clearly dependent on the direction of impact with respect to the crystallographic orientation of the quartz target. Maxima for the impact directions normal to {0001} and {10 $\bar{1}$ 0} cluster around the unit rhombohedron (Figs. 6 and 7), while maxima for impact normal to {10 $\bar{1}$ 1} are predominantly parallel to base and prism (Fig. 8).

A simple explanation of these results is illustrated in Figure 9. The experimentally produced cleavages form predominantly parallel to rational lattice planes which are close to 45° to the impact

SHOCK WAVE DIRECTIONS AND 45° SHEAR ANGLE

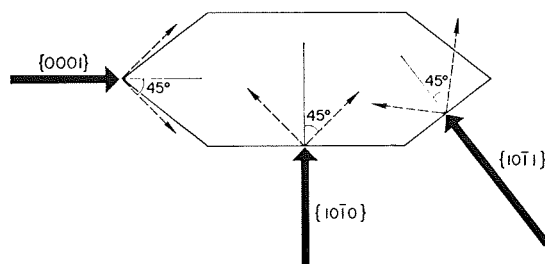


Fig. 9. Cross section through a quartz crystal with directions of impact (thick arrows) and geometrical 45° angle, indicating directions of highest shear stress (dashed arrows).

direction. If one assumes that, to a first approximation, quartz behaves as an isotropic medium and the compression in the direction of shock propagation is uniaxial, then the 45° angle would represent the direction of the highest shear stress. Refined calculations of the orientations of the maximum shear stress, taking into account the anisotropy of quartz, should be carried out.

There is clearly no doubt however, that in these studies all the "cleavages" are activated by shear forces. All cleavages are actually produced by faulting and are therefore "faults".

Whether the corresponding features in naturally shocked rocks are true cleavages or faults with small lateral displacements is hard to establish. Statistical measurements of Bunch *et al.*, (*this vol.*, p. 509.), Carter (1965, *this vol.*, p. 453), Robertson *et al.* (*this vol.*, p. 433) of "cleavages" and "faults" are remarkably similar and consistent with these experimental results.

In contrast to the above structures, the planar features have another mechanism of formation. All form more or less parallel to the same crystallographic planes regardless of the orientation of the shock wave. Their ease of development, however, seems to be dependent on the impact direction.

Microscopic observations of naturally and artificially shocked material suggest that planar features are lamellar-type optical discontinuities. Carter's electron microscope investigations (*this vol.*, p. 453) confirmed this for at least some samples. Engelhardt *et al.* (*this vol.*, p. 475) came

to similar conclusions from studies using the interference microscope. More detailed work is necessary to fully understand the nature of these planar structures and their mechanism of formation.

As Müller and Defourneaux (1968) pointed out, the only firm conclusions one can presently draw about the genesis of the planar features in quartz is that the final state of the shock wave compression has to reach the plastic curve of the equation of state. Planar features are thus produced only beyond the Hugoniot elastic limit where plastic deformation takes place. Plastic deformation is generally associated with gliding and possibly with permanent changes in the internal structure of the medium. The lamellar nature of the planar features possibly reflects destroyed lattice areas due to plastic gliding.

It is not known why gliding under shock loading conditions occurs predominantly on {10 $\bar{1}$ 3} and at higher pressures on {10 $\bar{1}$ 2}. Natural materials from impact sites, composed of randomly oriented quartz grains, also display planar features predominantly parallel to {10 $\bar{1}$ 3} and {10 $\bar{1}$ 2}, although in these cases all other rational planes are randomly oriented with respect to the propagating shock wave and are therefore equally suitable to act as potential gliding planes. Consequently, development of these planar features must be strongly controlled by the crystal structure.

The observations that "cleavage" occurs at low pressures and "planar features" parallel to {10 $\bar{1}$ 3} appear at lower pressures than do those parallel to {10 $\bar{1}$ 2} confirm the detailed work of Robertson *et al.* (*this vol.*, p. 433.) on natural materials from Canadian craters. They classified quartz in terms of progressive shock metamorphism by using the presence of cleavage only (Class I), and by the absence (Class II, type B) or presence (Class II, type D) of planar features parallel to {10 $\bar{1}$ 2}. Though their Class II, type A could not be verified in these experimental studies, their classification seems quite valid for describing the pressure-temperature history of individual quartz grains in a thin section.

REFRACTIVE INDEX MEASUREMENTS

Phase transitions are commonly observed in shock loaded materials. Petrological examination

of rocks which have been subjected to intense shock waves often indicates the presence of unique isotropic phases of component minerals, such as quartz and feldspar. Because the outlines of the original grain boundaries, cleavages, twin planes and other morphological details of the original crystalline material are preserved, one can conclude that a solid state reaction rather than melting took place. It appears likely that these isotropic phases were produced by the mechanical collapse of the crystal lattice to a high pressure phase during shock, followed by subsequent relaxation to a completely disordered phase which is optically isotropic and x-ray-amorphous. Engel-

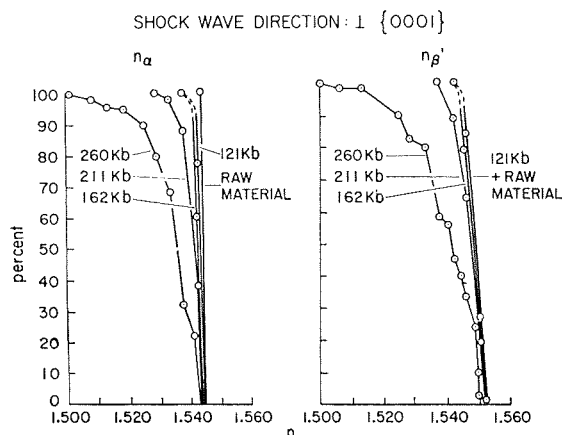


Fig. 10. Cumulative curves of refractive index measurements on quartz shocked at various pressures. Each point represents 50 measurements and indicates how many grains have higher refractive indices. Shock wave direction: $\perp \{0001\}$.

hardt *et al.*, (1967) termed these phases "diaplectic"; Chao (1967a) proposed the term "thetomorphic". The breakdown of the quartz lattice is gradual and the state of disorder is reflected by a decrease in refractive indices, loss of birefringence, lowered density, and altered x-ray powder patterns and IR-spectra (Engelhardt *et al.*, 1967; Bunch *et al.*, *this vol.*, p. 509; Chao, *this vol.*, p. 135; Engelhardt *et al.*, *this vol.*, p. 159).

Quartz, shock loaded to pressures above 250 kb, displayed an obvious loss of birefringence. Most recovered grains showed a variation in refractive indices, which is also very common in naturally shocked quartz; individual quartz grains are heterogeneous with regard to refractive indices and birefringence. These effects could result either

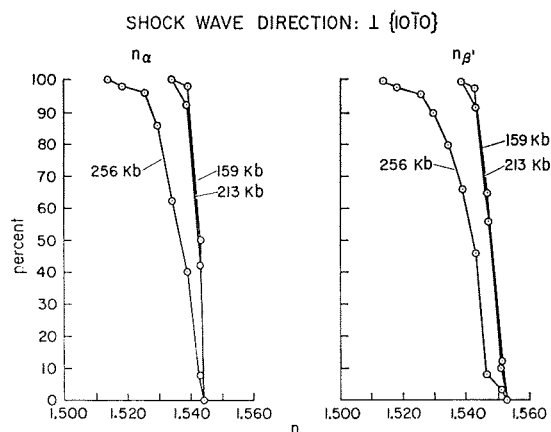


Fig. 11. Cumulative curves of refractive index measurements on quartz shocked at various pressures. Shock wave direction: $\perp \{10\bar{1}0\}$.

from real differences in shock damage or (probably to a much larger extent) from relative rotations of small lattice areas. Varying optical orientations may simulate different refractive indices and birefringence in an individual grain. Therefore, the refractive index measurements were conducted on grains 80–100 μ in size. At this scale the grains were fairly homogeneous. It turned out that the recovered samples were heterogeneous with regard to true differences in the degree of shock damage from grain to grain, and statistical measurements were therefore employed. The values of n_α and n_β' were determined relative to a series of refractive index liquids, using 50 randomly selected grains in each liquid.

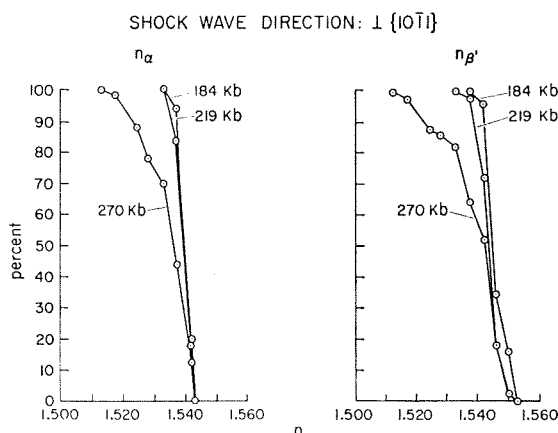


Fig. 12. Cumulative curves of refractive index measurements on quartz shocked at various pressures. Shock wave direction: $\perp \{10\bar{1}1\}$.

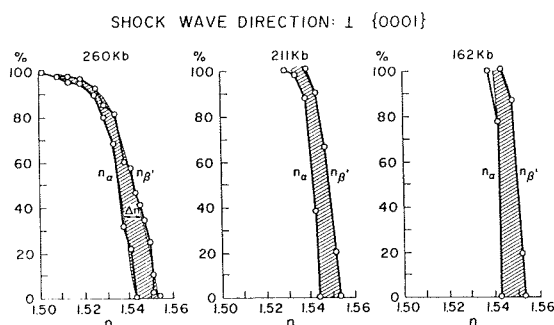


Fig. 13. Change in the birefringence of shocked quartz at various shock pressures. Shock wave direction: $\perp \{0001\}$.

The results of these statistical measurements are plotted in Figures 10, 11, and 12 as cumulative curves. In general, the refractive index begins to decrease above 200 kb. There are slight variations depending on orientation. Above 250 kb the optical properties are markedly changed. The complete breakdown of the quartz lattice could not be demonstrated, because the experimental setup did not permit higher pressures to be obtained. The available data indicate that pressures of at least 300 kb are necessary to produce complete lattice disorder. This is in fair agreement with the results of De Carli and Jamieson (1959) and Müller and Defourneaux (1968), who produced isotropic phases using single quartz crystals at pressures of 360 kb and 330 kb, respectively.

The differences in results for the three impact directions are probably due to the anisotropy of the quartz lattice in compressibility and especially in susceptibility to the development of planar features. The abundance of planar features is correlated with a lower mean refractive index, a relation which is also observed in naturally shocked material. This correlation may also indicate that the planar features are in fact "lamellae" and act as loci from which the breakdown of the quartz lattice spreads.

The change in birefringence may be determined from the cumulative curves of n_α and $n_{\beta'}$ as illustrated in Figure 13 for the impact direction $\perp \{0001\}$. The obvious relation shown is that a gradual loss of birefringence occurs with increasing pressure. Similar curves can be obtained for the other impact directions.

The reader is warned not to misinterpret the lower portion of the left diagram (Fig. 13; 260 kb). Although the measured curves for n_α and $n_{\beta'}$ are identical below $n=1.512$ this does not mean that the material is isotropic. The diagram only indicates that n_α and $n_{\beta'}$ differed by less than the increments of the refractive index liquids. All grains displayed birefringence and hence are not truly isotropic. The birefringence for the most highly damaged grains was $\Delta n = > 0.006$.

SUMMARY

Controlled shock loading experiments on quartz specimens having three different crystallographic orientations yielded various shock features observed in naturally shocked rocks.

(1) "Cleavages" develop at pressures below 50 kb. They are dependent on orientation and occur predominantly in the direction of highest shear stress. This demonstrates that, at least for these experiments, their formation mechanism is faulting.

(2) "Planar features" for all three impact directions are predominantly parallel to $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$. Their crystallographic orientation is insensitive to the propagation direction of the shock wave. They are only formed in the plastic region of the quartz equation of state, with $\{10\bar{1}3\}$ orientations produced by pressures exceeding 100 kb and $\{10\bar{1}2\}$ orientations by pressures above 160 kb. Their formation requires extreme stress and strain rates which are very unlikely to occur at the earth's surface under any other conditions but meteorite or cometary impact.

(3) The breakdown of the quartz lattice as reflected by its refractive index begins at about 200 kb and is already pronounced at 250 kb. The formation of diaplectic quartz phases probably requires about 300 kb. The breakdown of the quartz lattice is gradual over a pressure range from 200 kb to at least 300 kb.

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REFERENCES

- Ahrens, T. J., and V. G. Gregson, Jr., Shock compression of crustal rocks: data for quartz, calcite, and plagioclase rocks, *J. Geophys. Res.*, **69**, 4839–4874, 1964.
- Bloss, D. F., Anisotropy of fracture in quartz, *Am. J. Sci.*, **255**, 214–255, 1957.
- Bunch, T. E., and A. J. Cohen, Shock deformation of quartz from two meteorite craters, *Bull. Geol. Soc. Am.*, **75**, 1263–1266, 1964.
- Bunch, T. E., A. J. Cohen, and M. R. Dence, Shock-induced structural deformation in plagioclase and quartz, *this vol.*, p. 509.
- Carter, N. L., Basal quartz deformation lamellae—a criterion for recognition of impactites, *Am. J. Sci.*, **263**, 786–806, 1965.
- Carter, N. L., Dynamic deformation of quartz, *this vol.*, p. 453.
- Chao, E. C. T., Shock effects in certain rock-forming minerals, *Science*, **156**, 192–202, 1967a.
- Chao, E. C. T., Impact metamorphism, in *Researches in geochemistry*, v. 2, P. H. Abelson ed., pp. 204–233, New York, John Wiley and Sons, 1967b.
- Chao, E. C. T., Pressure and temperature histories of impact metamorphosed rocks—based on petrographic observations, *this vol.*, p. 135.
- De Carli, P. S., and J. C. Jamieson, Formation of an amorphous form of quartz under shock conditions, *J. Chem. Phys.*, **31**, 1675–1676, 1959.
- Dence, M. R., Shock zoning at Canadian craters: petrography and structural implications, *this vol.*, p. 169.
- Engelhardt, W. v., Die Anisotropie der Teilbarkeit des Quarzes, *Akad. Wiss. Göttingen, Math.-Phys. Kl.*, **43**–56, 1944.
- Engelhardt, W. v., J. Arndt, D. Stöffler, W. F. Müller, H. Jeziorkowski, and R. A. Gubser, Diaplektische Gläser in den Breccien des Ries von Nördlingen als Anzeichen für Stosswellenmetamorphose, *Contr. Mineral. and Petrol.*, **15**, 93–102, 1967.
- Engelhardt, W. v., F. Hörz, D. Stöffler, and W. Bertsch, Observations on quartz deformation in the breccias of West Clearwater Lake, Canada, and the Ries Basin, Germany, *this vol.*, p. 475.
- Engelhardt, W. v., and D. Stöffler, Spaltflächen im Quarz als Anzeichen für Einschläge grosser Meteoriten, *Naturwiss.*, **17**, 489–490, 1965.
- Engelhardt, W. v., and D. Stöffler, Stages of shock metamorphism in the crystalline rocks of the Ries Basin, Germany, *this vol.*, p. 159.
- Fowles, G. R., Dynamic compression of quartz, *J. Geophys. Res.*, **72**, 5429–5742, 1967.
- Gold, D. P., A study of quartz subfabrics from the Brent crater, Ontario, *this vol.*, p. 495.
- Isbell, W. M., F. H. Shipman, and A. H. Jones, Hugoniot equation of state measurements for selected geological materials, *GM Defense Res. Lab. Quart. Progr. Rept. No. 1*, 1966.
- Jones, A. H., W. M. Isbell, and C. J. Maiden, Measurement of the very high pressure properties of materials using a light gas gun, *GM Defense Res. Lab. T. R.*, **65**–84, 1965.
- Müller, W. F. and M. Defourneaux, Deformationsstrukturen in Quarz als Indikator für Stosswellen: eine experimentelle Untersuchung an Quarzeinkristallen, *Z. Geophys.*, 1968, in press.
- Robertson, P. B., M. R. Dence, and M. A. Vos, Deformation in rock-forming minerals from Canadian craters, *this vol.*, p. 433.
- Scar, C. B., N. M. Short, and G. G. Cocks, Shock-wave damage in quartz as revealed by electron and incident-light microscopy, *this vol.*, p. 483.
- Short, N. M., Shock processes in geology, *J. Geol. Education*, **14**, 149–163, 1966.
- Short, N. M., and T. E. Bunch, A worldwide inventory of petrologic features characteristic of rocks associated with presumed meteorite impact craters, *this vol.*, p. 255.
- Stöffler, D., Neuere Erkenntnisse in der Tonsteinfrage auf Grund sediment-petrographischer Untersuchungen im Flöz Wahlschied der Grube Ens Dorf (Saar), *Beitr. Min. Petr.*, **9**, 285–312, 1963.
- Stöffler, D., Zones of impact metamorphism in the crystalline rocks of the Nördlinger Ries crater, *Contr. Mineral. and Petrol.*, **12**, 15–24, 1966.
- Thiel, M. v., Compendium of shock wave data, United States Atomic Energy Commission, Division of Technology, Lawrence Radiation Laboratory, Livermore, Calif., Publication UCRL-50108, 1966.
- Wackerle, J., Shock wave compression of quartz, *J. Appl. Phys.*, **33**, 922–937, 1962.